

LIMITING ACCURACY OF MARS, MERCURY, VENUS INSTANTANEOUS SPIN COMPONENTS ESTIMATION BY GROUND-BASED RADAR. I. V. Holin, Space research institute, Moscow, holin@mail.cnt.ru

Introduction: It took a long time to understand how rotational dynamics of nearest to Earth terrestrial planets could be studied by ground-based radar in much more details. Various techniques based on delay-Doppler imaging and VLBI imaging using a radar transmitter have accuracies limited to resolution. E.g. a 1.5 km resolution was achieved during delay-Doppler imaging experiments on Mercury with the Arecibo radar [1]. At best it might lead to several arcminutes uncertainty in determination of the pole direction. Ground-based VLBI may have angular resolution as high as 10^{-9} rad, i.e. ~ 100 m on Mercury's surface, but we are unable to detect this very weak echo. In practice imaging techniques do not reach even these limits and until now coordinates of the north pole of Mercury have not been improved reliably with respect to the Mariner 10 uncertainty: ± 6.5 deg in obliquity and ± 2.6 deg in precession angle [2]. Some radar experiments were consistent with zero obliquity [3] but the value 0.5 ± 0.4 deg were obtained as well [4] while the theory says that obliquity can be as small as a few arcminutes [5]. Repeat orbit radar interferometry (RORI) was proposed to measure Mercury's obliquity and possibly librations [6-8]. RORI is inter-year on principle and may suffer from the relatively few opportunities when the geometries of inter-year radar observations are nearly identical [5].

Ground-based imaging techniques prevent us from the very detailed investigation of planetary spin dynamics on two reasons: 1) the above limits in accuracy are too rough to sense variations in rotational velocity and pole orientation, 2) measuring interval is compared to or exceeds the rotational period what demands the exact apriori model of variations to interpret observations adequately. To obtain full information on spin dynamics including variations which may be partially apriori unknown or stochastic we need a technique allowing precise measurement of instantaneous spin components. In other words we have to improve accuracy by 3 to 4 orders of magnitude with respect to radar techniques now in use (from ~ 1 deg to ~ 1 arcsec level or better) and simultaneously cut the measuring time by 5 to 6 orders of magnitude (from years to minutes). Let us see if it is possible.

Statistical synthesis: At cm wavelengths planetary surfaces can be considered randomly rough making scattered radar fields to have Gaussian distribution with zero average. Such fields are fully described by the space-time correlation (covariation) function (matrix)

CF. Applying the statistical synthesis procedure to CF under given (e.g. Maximum Likelihood) criterion one can find the optimum processing algorithm (OPA) which shows the best possible way of radar echoes processing to minimize estimation errors. OPA can then be used to find the limiting accuracy of estimation of a certain parameter encoded by Nature into radar fields. Space-time CF properties were discussed in [9] while OPA and the limiting accuracy of instantaneous spin components estimation were derived in [10]. The result of that work was proposition of a new radar technique named radar speckle displacement interferometry (RSDI) discussed at length in [11,12,18,19].

RSDI limiting accuracy: RSDI technique is based on the speckle displacement (far coherence) effect and is aimed at precision measurement of instantaneous spin-vector components and their variations with time. It does not construct any image of an object and taken alone can not give coordinates of features on its surface but it may give much more precise unambiguous instantaneous pole coordinate(s) in the sky [13] and instantaneous rotational velocity allowing estimation of any variations with time.

The limiting RSDI accuracy (rms) of instantaneous spin components estimation under monochromatic illumination is [10]

$$\sigma = \frac{l}{q} \frac{v}{b v_{\Omega}} \quad (1)$$

where l is the correlation radius of scattered radar field, q is the resulting amplitude SNR at the correlator output, b is the interferometer baselength, v is the velocity of speckle displacement, and v_{Ω} is the part of v caused by the rotation only. As shown in [10] Eq. (1) is consistent with the limiting accuracy of time delay estimation of stochastic signals.

In accordance with Eq. (1) limits for Mercury, Venus, and Mars with the Goldstone ~ 450 KW transmitter and the Goldstone – Green Bank receiving interferometer are as follows (λ – transmitted wavelength).

Mercury: $\sigma \sim 1.5$ arcsec [11,14], $\lambda = 3.5$ cm.

Venus: $\sigma \sim 0.5$ arcsec [15], $\lambda = 13$ cm.

Mars: $\sigma \sim 1$ arcsec, $\lambda = 3.5$ cm.

The situation about Moon is much more specific due to its synchronous motion with respect to Earth. As discussed in [16,17] about 1 arcsec accuracy can be

achieved on Moon as well. Speckles from Mercury, Venus, and Mars sweep across the surface of Earth at velocities $\sim 250 \text{ km s}^{-1}$, $\sim 20 \text{ km s}^{-1}$, $\sim 11,000 \text{ km s}^{-1}$ respectively so measurement times with interferometers like Goldstone – Green Bank for Mercury and Mars are within $\sim 1 \text{ min}$ and for Venus within $\sim 3 \text{ min}$ (propagation times are excluded). Unfortunately observation times at receiving positions in any case are within $\sim 1 \text{ min}$ and can not be increased to improve accuracy because rotation of Earth separates baseline orientation from the speckle displacement direction rather quickly.

The implication of the statistical synthesis results is that there exists no other ground-based radar technique to measure planetary instantaneous spin components which may overcome RSDI limits in accuracy presented by Eq. (1) until we are forced to consider rough planetary surfaces as randomly rough and, as a consequence, speckled scattered radar fields as randomly speckled. Also for hard objects the surface of which does not change with time we found no improvements with modulated waveforms because all range layers give exactly the same speckle velocities.

Experiments: Most probably the first RSDI experiment was discussed in [10] about Venus for the Evpatoria (Crimea, the former USSR, now Ukraine) – Ussuryisk (Far East of Russia) radar interferometer ($b \sim 6,000 \text{ km}$) but the approach was not understood at that time and has not been understood in Russia until present. Later a number of possible RSDI experiments were proposed about Mercury to estimate its obliquity and librations with the existing radar facilities around the world [14,18-20]. Attempts with the Evpatorian transmitter were not so successful [21] partially because the equipment was designed for VLBI observations. In accordance with the RSDI principle [19] the main idea of the experiments in the vicinity of May 2002 inferior conjunction was measurements of obliquity and librations [20]. As applied to the Goldstone – Green Bank (G-GB) radar interferometer this means that the radar echo from Mercury received at the Green Bank 100 m radio telescope should be correlated with the echo at the Goldstone 70 m radar taken $\sim 11\text{--}13 \text{ s}$ later (the time needed by speckles to travel from Green Bank to Goldstone). Using this fundamental approach J.-L. Margot et al. carried out successful experiments on Mercury in May-June 2002 with the G-GB interferometer (USA) [22]. Strong correlation was clearly detected on all the four dates of the experiments showing that speckles really were travelling in nearly "frozen" state [22,23]. The May-June 2002 G-GB experiments on Mercury can be considered as the first in History reliable confirmation of the "frozen" speckle displacement (far coherence) effect in planetary radar astronomy. Theoretical limits for those experiments were discussed in [11]. At

present the improvement in accuracy on Mercury's obliquity is expected about 3 orders of magnitude [22] while the limiting RSDI accuracy, that corresponds to the OPA, is about another order of magnitude higher [11,12]. Further efforts should be undertaken to improve accuracy to the OPA limits Eq. (1). In case of success a number of fundamental problems can be studied effectively by the existing ground-based radar, radio, and radio communication facilities. Among these problems there are constraints on the interior of Mercury, angular momentum exchange between Venus' atmosphere and the planet itself, nutations of polar axis of Mars connected with its constitution and all other problems related to spin dynamics of Mercury, Venus, and Mars. We hope RSDI experiments about Venus, Mars, and Moon are upcoming as well.

References: [1] Harmon J. K. et al. (2001) *Icarus*, 149, 1 [2] Klaasen K. P. (1976) *Icarus*, 28, 469 [3] Harmon J. K. et al. (1994) *Nature*, 369, 213 [4] DeVries C. H. and Harmon J. K. (1994) *AAS meeting*, 26, 1376 [5] Peale S. J. et al. (2002) *Meteoritics & Planet. Sci.*, 37, 1269 [6] Slade M. A. et al. (1998) *DPS meeting*, 5005 [7] Slade M. A. et al. (1999) *LPS XXX*, Abstract # 1143 [8] Slade M. A. et al. (2001) *Mercury Meeting*, abstract # 8062 [9] Holin I. V. (1988) *Radiophysics & Quant. Electron.*, 31, 515 [10] Holin I. V. (1992) *Radiophysics & Quant. Electron.*, 35, 433 [11] Holin I. V. (2002) *Solar System Res.*, 36, 206 [12] Holin I. V. (2003) *Meteoritics & Planet. Sci.* (in revision) [13] Holin I. V. (2002) *Met. Soc.*, 65, 5041 [14] Holin I. V. (2002) *LPS XXXIII*, Abstract # 1387 [15] Holin I. V. (2002) *Solar System Remote Sensing*, LPI Contribution No. 1129, 33 [16] Holin I. V. (2002) *LPS XXXIII*, Abstract # 1393 [17] Holin I. V. (2002) *Moon Beyond 2002*, 3030 [18] Holin I. V. (1998) *Uspekhi Sovrem. Radioelek.*, No. 4, 3 [19] Holin I. V. (1999) *Uspekhi Sovrem. Radioelek.*, No. 7, 16 [20] Holin I. V. (2001) *Mercury Meeting*, abstract # 8038 [21] Holin I. V. (2002) *Met. Soc.*, 65, 5131 [22] Margot J. L. et al. (2002) *Eos Trans. AGU*, 83(47), Fall Meet. Suppl., Abstract P22D-08 [23] Holin I. V. (2002) *Solar System Remote Sensing*, LPI Contribution No. 1129, 35